

Introduction

The study area includes the proposed reservoir areas of the Red Bank, Thomes-Newville, Sites, and Colusa Projects along the west side of the Sacramento Valley between Maxwell and Red Bluff. The four projects shown on Figure 1 are being evaluated for offstream storage opportunities using water from the Sacramento River and its tributaries. Surplus water would be diverted into the reservoirs during periods of surplus flows and released when needed.

Faults and earthquakes affect dams in several different ways. Active faults in the foundation may displace elements of the dam either by slow creep or by sudden movement during earthquakes. Seepage and piping may be induced, resulting in failure of the dam. Shaking during an earthquake may also cause fracturing of the dam, or may cause the dam to slide, settle, liquefy, or separate from its foundation. In some cases, earthquake shaking and landsliding into the reservoir may cause wave action (seiches - the oscillation of a lake in large, slow waves), erosion of the dam face, and overtopping.

Dams in earthquake prone areas generally require a more conservative embankment section and foundation treatment. A more conservative embankment section may include more freeboard, better or thicker filters and drains to reduce pore pressure, thicker impervious cores of piping-resistant material, rockfill toes for slope support, and flatter slopes. New criteria developed by the Department of Water Resources' Division of Safety of Dams require that the outlet works and spillway must be capable of evacuating 10 percent of the maximum water depth within 10 days. This modification is designed to increase safety should the dam be compromised during an earthquake. Design details of embankment type dams can make an enormous difference in whether they are inherently safe from earthquake damages (Sherard, et al., 1963).

Foundation work may include additional stripping, removal of all soil and weathered rock material, and cleaning and dental work to include excavation of faulted material, deeper cutoff trenches, and concrete fill in weak areas. This type of foundation work will prevent loose soil from liquefying and moving out from underneath the dam and from causing cracking, sliding or actual horizontal displacement of the dam.

Proposed Projects

Four projects are being considered. From north to south, they are the Red Bank, Thomes-Newville, Sites, and Colusa Projects. Each one has a number of storage capacity options.

The Red Bank Project, located about 15 miles west of Red Bluff, was first identified in Bulletin 3, the California Water Plan (DWR 1957). It consists of two dams: Dippingvat on south fork Cottonwood Creek and Schoenfield on Red Bank Creek. Excess flows from the South Fork would be diverted through a series of conveyance facilities into the larger Schoenfield Reservoir. Total storage capacity is 358,700 acre-feet. A fault and seismic investigation was completed by DWR in 1991.

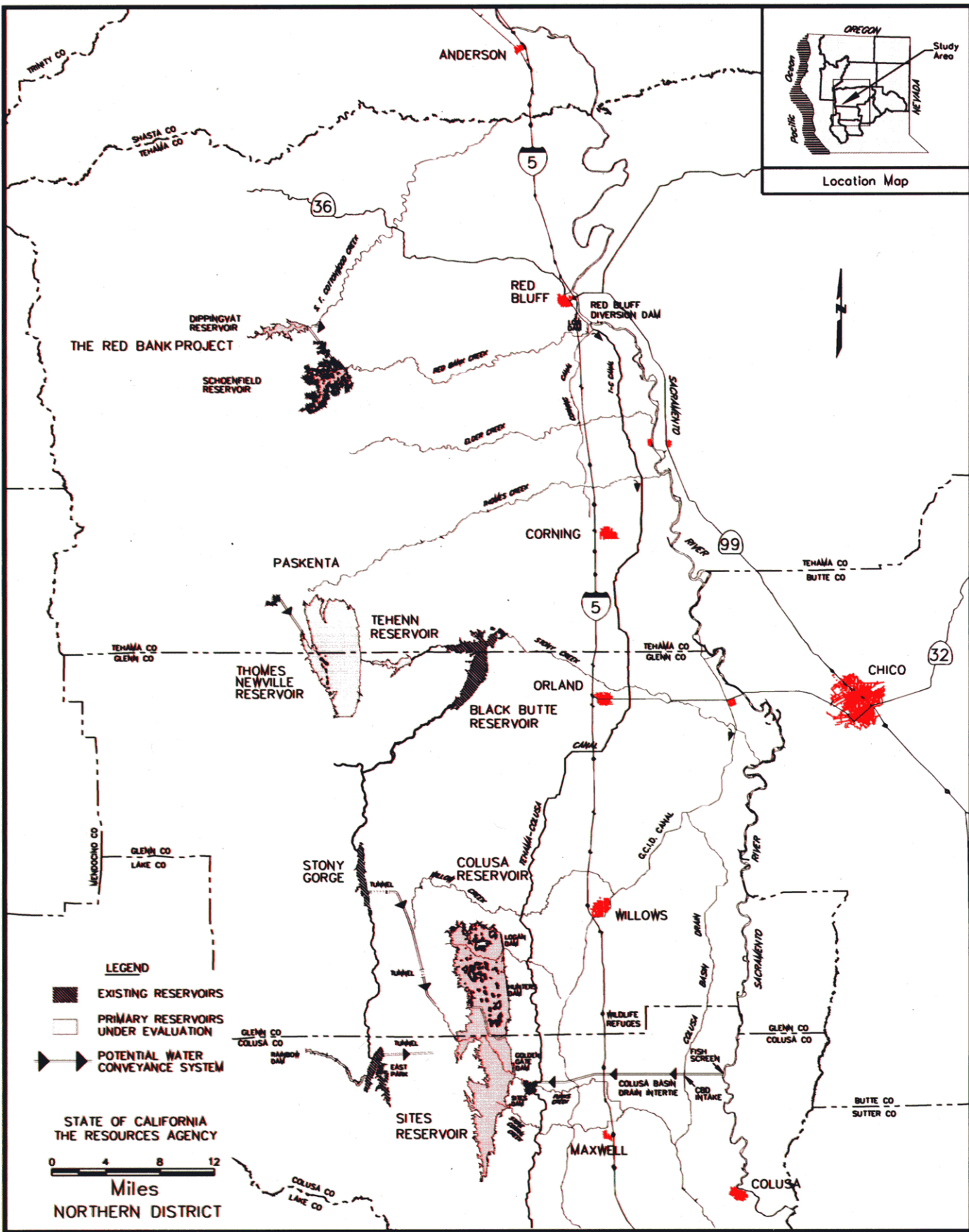


Figure 1. Location Map of Proposed Offstream Storage Projects.

The Thomes-Newville Project, located about 20 miles west of Corning, would provide instream storage for north fork and main stem Stony Creek, and offstream storage for the Sacramento River. Facilities include Newville and Tehenn reservoirs on the north fork, a diversion facility from Thomes Creek to Newville, a two-way conveyance facility between Tehenn and the existing Black Butte Reservoir on Stony Creek, and a two-way canal between the Tehama-Colusa Canal and Black Butte Reservoir. The canal would bring in Sacramento River water. Two storage capacities, a 1.84 million acre-foot smaller facility and a 3.08 maf larger facility, are being considered. Earth Sciences Associates completed a fault and seismic investigation for DWR in 1980.

The Sites and Colusa Projects, located about 10 miles west of Maxwell, would provide offstream storage for the Sacramento River. Water would be conveyed via the Tehama Colusa Canal, Glenn-Colusa Canal, and/or a new cross-valley canal. There are three alternative sizes being considered: a 1.2 maf smaller Sites, a 1.9 maf larger Sites, and a 3.3 maf Colusa Reservoir. The smaller and larger Sites would have a Sites Dam on Stone Corral Creek, Golden Gate Dam on Funks Creek, and up to 12 saddle dams around the reservoir rim.

The Colusa facility would extend the larger Sites into the northern “Colusa Cell.” Additional facilities include Hunters Dam on Hunters Creek, Logan Dam on Logan Creek, and about five saddle dams along the north rim of the reservoir. The smaller Sites was investigated by the U.S. Bureau of Reclamation (1969), but their study did not include the larger Sites or Colusa. Golden Gate Dam has several possible axial alignments: an upstream straight alignment, a downstream curved alignment, and a downstream straight alignment.

Purpose and Scope

The study purpose is to identify the potential for tectonic activity along the west side of the Sacramento Valley and to determine fault and seismic hazards affecting the feasibility of the proposed projects.

The work has been divided into two phases. Phase I includes a literature survey and discussion of faulting and seismicity based on available knowledge. Phase I will guide the implementation of Phase II, which will include fieldwork such as mapping, trenching, and drilling. The purpose of Phase II is to conduct field investigations to determine the extent and activity level of faulting within the project area and to develop seismic design parameters for project features. The Phase II report will be published under separate cover at a later date.

The Phase I scope includes the following tasks:

- Review previous work. This includes a literature and Internet search of pertinent information relating to dams and fault and seismic hazards.
- Conduct literature searches and compile known fault zones near the reservoir areas. Determine “not-significant,” “potential,” and “significant” sources of seismic activity. Compile estimated seismic and ground breakage risks from these sources.
- From published information determine the presence of faults in dam foundations. Compile any existing subsurface exploration statistics to determine extent of fracturing and date of last activity.

- Compile a preliminary earthquake map from DWR's Earthquake Engineering Section epicenter data set.
- Work with the U.S. Geological Survey to produce an analysis of the Red Bluff Microseismic Network data.
- Provide a summary, conclusions, and recommendations section to guide implementation of Phase II.

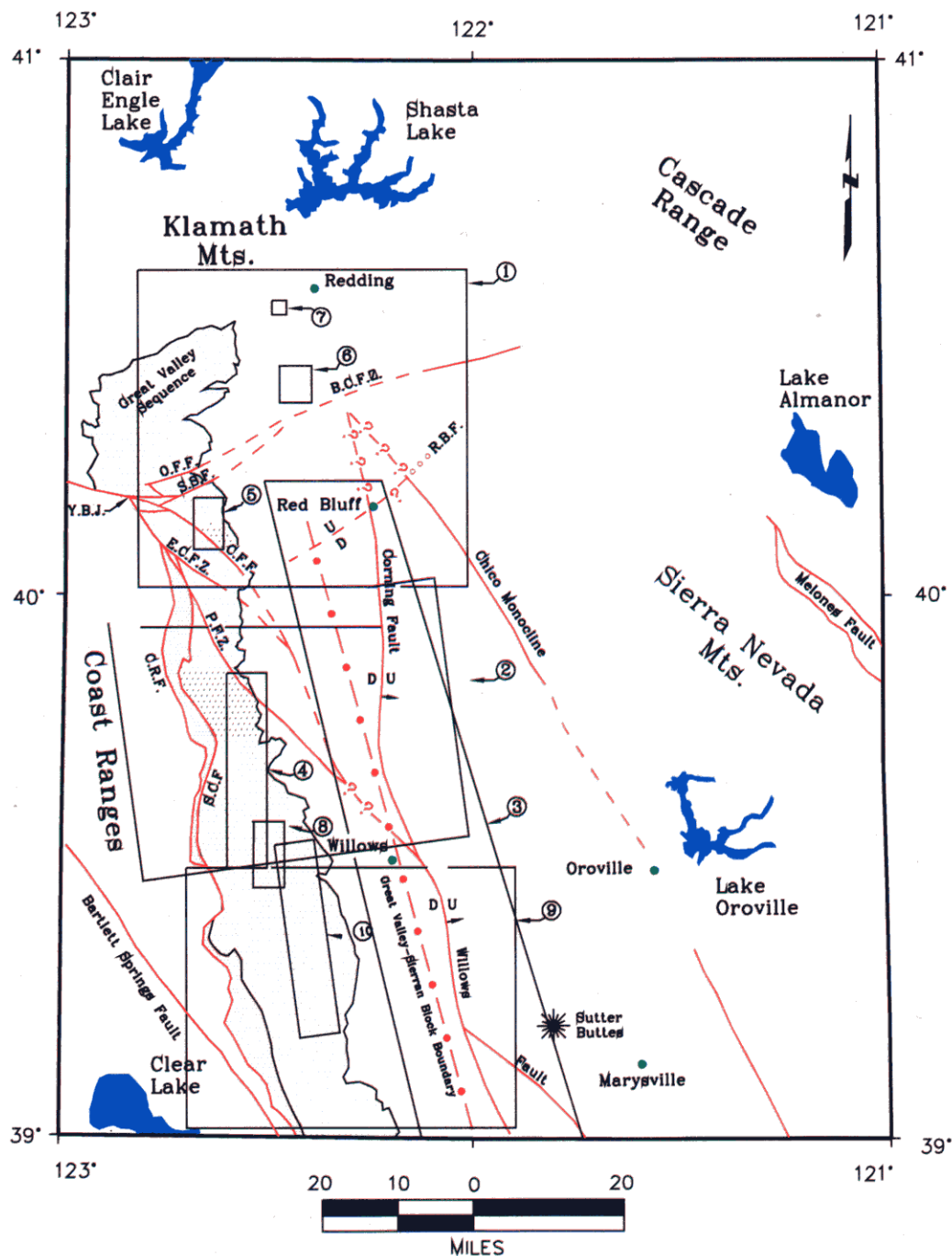
Seismic parameters were investigated for all four projects. The recent work done at the Red Bank and Thomes-Newville Projects, and the older work done at the Sites and Colusa Projects were compiled from a variety of sources and presented in Attachment A to this report.

As required by the State of California, Department of Conservation, Division of Mines and Geology (1997), this preliminary fault and seismic investigation was prepared and reviewed by Certified Engineering Geologists.

Previous Investigations

A large amount of work has been done on fault and seismic hazards along the west side of the Sacramento Valley. Figure 2 shows the location of geologic mapping by various workers. Most of this mapping is 10 to 20 years old. Recent advances in our knowledge of the tectonic framework have greatly increased our understanding of the potential for large earthquakes in the area. Pertinent investigations include:

- Brown and Rich, 1961. USGS personnel mapped the geology of the Lodoga 15-minute quadrangle.
- USBR, 1969. USBR conducted a fault investigation of the Sites project. Faults were mapped in the foundation areas of Sites and Golden Gate Dam sites and within the reservoir areas.
- DWR, 1978. A preliminary fault and seismic study of the Glenn Reservoir Complex concluded that there was no evidence of Quaternary fault activity near the proposed reservoir. Seismic activity suggested that faults were active to the west. DWR assigned an MCE of local magnitude (M_L) 7 to the entire west side based on two 1892 Winters-Vacaville earthquakes that occurred 70 miles to the south. The earthquake magnitude was based on a "floating" event and not on any particular fault.
- Earth Science Associates, 1980. ESA conducted this study for DWR's Glenn Reservoir Complex and concluded the following: surface fault activities on all faults in the area are older than 30,000 years, all the transverse faults are pre-Quaternary in age and do not present offset hazards, the probability of reservoir-induced seismicity is low, and that movement occurred on the Stony Creek fault between 30,000 and 130,000 years ago.
- DWR, 1980. A field study of apparent movement on the Stony Creek fault suggests that the movement was caused by landsliding and not faulting.



Legend

Map Symbols



Fault: letters U and D indicate upthrown and downthrown sides. Faults are dashed where approximately located, dotted where concealed, and queried where location is uncertain. Arrow indicates direction of dip.



Coast Ranges-Sierran Block Boundary (Great Valley Fault)



Coast Range Ophiolite.



Great Valley Sequence

Faults

R.B.F. = Red Bluff Fault
C.F.F. = Cold Fork Fault Zone
C.R.F. = Coast Range Fault
E.C.F.Z. = Elder Creek Fault Zone
S.C.F. = Stony Creek Fault
P.F.Z. = Paskenta Fault Zone
S.S.F. = Sulphur Springs Fault
O.F.F. = Oak Flat Fault
B.C.F.Z. = Battle Creek Fault Zone
Y.B.J. = Yolla Bolly Junction

Source: Faults plotted from Horwood 1986 and Blake et al., 1984

Previous Studies

- ① HMT Study Area (1983)
- ② ESA Study Area (1980)
- ③ Wong et. al., (1988)
- ④ Glenn Reservoir/Thomes-Newville
- ⑤ Red Bank Project area
- ⑥ Dutch Gulch/Tehoma Dam Sites
- ⑦ Misselbeck Dam
- ⑧ Stony Gorge Reservoir
- ⑨ WLA and Associates, 1997
- ⑩ DWR Sites and Colusa Study Area

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
NORTHERN DISTRICT

FAULT AND SEISMIC HAZARDS - PHASE I

RED BANK, THOMES-NEWVILLE, BUTTE, AND COLUSA PROJECTS

Previous Studies
Northern California

- USBR, 1981. The Stony Creek fault was assessed based on a seismic hazard reevaluation of Stony Gorge Dam, a few miles southwest of the Thomes-Newville Project. The USBR agreed with ESA on the seismic potential of local and regional faults, but felt that the trenching along the Stony Creek fault was inconclusive due to the unverified terrace ages. The USBR assigned a MCE of 6 to a regional event with an epicentral distance of about 5 miles and a focal depth of about 6 miles.
- DWR, 1980, Appendix A of the Thomes-Newville final report. This report included a summary of findings to date. It also included a resolution of the discrepancies regarding recent activity along the Stony Creek fault by concluding that last movement occurred more than 130,000 years ago. The maximum probable horizontal ground acceleration was estimated to be 0.55 gravity.
- Harlan, Miller, and Tait, 1983. The fault and seismic potential of the U.S. Army Corps of Engineers' Cottonwood Creek Project was considered. This project is about 10 miles northeast of the Red Bank Project. Their study included a detailed mapping of Quaternary geology within a 20-mile radius of the proposed dams and a summary of seismic parameters for the project. HMT concluded that no recognizable surface faulting has occurred in the last 125,000 years and surface faulting is not a concern. Reservoir-induced seismicity (RIS) risks were also assumed to be low. A review of the HMT report was used to determine the Cottonwood Creek Project maximum expected peak horizontal ground acceleration (0.5g) and velocity (30 cm\second) for the three most probable seismic sources.
- Walter, 1986. A study of intermediate focus earthquakes in the Weaverville to Red Bluff area further defines the extent of the subducted Gorda plate and Cascadia subduction. The earthquakes also open up the possibility that a magnitude (M) 8+ could occur directly under the Red Bank Project.
- Wong, Ely, and Kollmann, 1988. This study defined the Coast Ranges-Sierra Nevada Block Zone as a fundamental tectonic boundary capable of moderate to major earthquakes. This zone is a complex region of active compressional tectonics extending along the western margin of the greater Central Valley from Coalinga to Red Bluff. It is probably responsible for the two 1892 Winters (M_L 6-7) and the 1983 Coalinga (M_L 6.7) earthquakes. The potential for large earthquakes exists along the entire boundary, but the low level of seismicity prevented a definitive characterization of the northern region.
- DWR, 1991. Based on accelerations experienced from the Coalinga aftershocks, DWR estimates a 0.55g peak acceleration for the Red Bank Project.
- Unruh and Moores, 1992. A study of the southwest Sacramento Valley defines the relation between surface deformation and earthquake potential from presently active, blind-thrusting activity associated with the CRSNBZ.

- California Department of Transportation, 1996. Publication of a technical report and deterministic seismic hazard map for California was based on MCEs.
- Department of Conservation, Division of Mines and Geology and U. S. Geological Survey, 1996. As part of the Working Group on Northern California Earthquake Potential, both agencies published a database on the sources for earthquakes larger than M6.
- William Lettis and Associates, 1997. The consultant published a seismotectonic evaluation of Monticello, Stony Gorge, and East Park Dams for USBR.

Methods of Investigation

The following activities were conducted for Phase I of this study, which evaluates and summarizes existing information but does not include any new field investigations:

- Literature and Internet reviews and searches were incorporated into a preliminary review of available fault, seismic, and tectonic interpretation data.
- Seismic data from USGS, CDMG, and DWR were collected and integrated into maps. Seismic data in the Red Bank Project region were collected and analyzed by USGS (Attachment A).
- Information on local and regional faulting was summarized. Faults that have the potential of affecting the proposed structures were evaluated.
- Geologic maps, fault maps, and cross-section drawings were prepared using existing data. Both regional and localized geologic mapping were compiled.
- Preliminary conclusions regarding fault and seismic safety design requirements were developed. Recommendations for further work are presented.
- A final report with plates, tables, and figures was prepared summarizing the investigation.

Phase II will include the following:

- Detailed fault mapping of foundation areas for the proposed structures. Most of the mapping will be for the Sites and Colusa Projects, since DWR has already done detailed mapping of the Thomes-Newville and Red Bank Projects.
- Detailed fault mapping of the Salt Lake fault. The Salt Lake fault extends over 40 miles and is one of the larger features of concern.
- Conducting regional photographic analyses along the western foothills of the Sacramento Valley. Stereo-aerial photographs will be viewed to identify lineaments for further field investigation. Low-sun-angle photography and side-looking radar analyses will also be incorporated into Phase II.

- Mapping Quaternary stream terraces to determine age and deformational history.
- Topographic and total station surveying to determine Quaternary to Holocene deformation.
- Analyzing earthquake information to determine potential seismic sources, peak accelerations, attenuation relations, directivity effects, response spectra, time histories, and ground motion parameters for dam stability evaluations.
- Diamond core drilling in the foundation of proposed structures. The drill holes will intersect faults at depth to evaluate fault activity, fracturing, foundation material strength, and permeability.
- Trenching across faults and suspected faults. This will determine fault locations and widths, and provide evidence and age of recent movement.
- Preparing a report with the results of the study.

Definition of Terms

The following includes a brief discussion of some of the terms that are used in this report.

Richter Magnitude - M , is a measure of the strain energy released by an earthquake. It is derived by studying the seismographic record. It is expressed in Arabic numerals and is a single number for an earthquake that does not relate to such factors such as damage or distance from the epicenter. The concept was introduced by C.F. Richter, who first applied it to Southern California earthquakes. The magnitude scale is logarithmic, to the base 10, of the amplitude, in microns, of the largest trace deflection that would be observed on a standard torsion seismograph, at a distance of 100 kilometers from the epicenter. The difference in terms of the total energy released between successive magnitudes such as an $M1$ and an $M2$, and between an $M7$ and an $M8$ is about 30 times greater. There are several variants to the scale, including:

local magnitude - M_L .

surface magnitude - M_s , based on the amplitude of the surface waves.

moment magnitude - M_w , that takes into account all the seismic waves present, which is now the most widely used. The M_w can also be estimated using the length or surface area of a fault plane. The calculated M_w may be used to define potential earthquake magnitudes from active faults with a limited seismic record.

Maximum credible earthquake - MCE, the largest possible earthquake that could reasonably be expected to occur in a given area on a given fault. The MCE is based on historic quakes, location of faults in the vicinity, and the general tectonic framework of the region. The MCE is generally somewhat larger than the calculated M_w since it is prudent to assume that more than one fault segment may move at one time.

Design Earthquake - the potential magnitude for which the dam should be designed to withstand during its lifetime. The MCE is chosen as the Design Earthquake for large structures and for areas where structural failure would have dire consequences.

Peak ground acceleration - PGA, and

Peak horizontal ground acceleration - PHGA, are the highest acceleration measured during a seismic event. The PGA and the PHGA for a particular site can also be calculated based on (1) the distance from the presumed hypocenter and (2) various attenuation models.

Reservoir-Induced Seismicity - RIS, is seismicity induced by the filling of large and deep reservoirs .

Earthquake intensity is a rating of the effects of an earthquake on man and his environment. It varies with distance from the epicenter, the type of ground, and the type of damage that occurs. Scales that have been used include:

Rossi-Forel with a scale from 1 to 10.

Mercalli, and the **Modified Mercalli** - MM, with the latter the most common. The MM scale ranges from Roman Numerals I to XII, with I not felt and XII nearly total destruction.

Summary and Conclusions

There are a number of types of earthquakes that need to be considered to evaluate earthquake risk. These are random earthquakes not associated with any known faults, MCEs calculated for active faults, and RIS. There are also earthquake-related hazards such as liquefaction, subsidence, and surface rupture that need to be considered.

Random Earthquakes

Random earthquakes occur with no correlation to known geologic structures, either mapped on the surface or detected by subsurface geophysical methods. Many of the background seismic events fit this definition. A conservative magnitude is selected by evaluating the earthquake history for the period of record. Several M5 and above earthquakes have occurred in the Sacramento Valley. An M5.4 with numerous strong aftershocks occurred recently in the Redding area. An M5.7 occurred in the eastern foothills near Oroville in 1975. In the 1880s two M5 earthquakes occurred near Red Bluff. The random earthquake selected for the westside Sacramento Valley projects is an M6.5 occurring anywhere within the project areas, including directly under the damsites. This is larger than historic random earthquakes and is believed to be conservative.

Maximum Credible Earthquake

Table 1 shows the design parameters selected for the four projects. These parameters are believed to be conservative.

Table 1. Draft Preliminary Design Parameters for the Proposed Projects*

Project	Maximum Credible Earthquake (M _w)	Distance (km)	Depth (km)	Peak Acceleration (g)	Duration (seconds)	Period (seconds)
Sites and Colusa	7	0	10	0.7	26	0.32
Thomes-Newville	7	0	10	0.7	26	0.32
Red Bank	8.3	0	35	0.72	28.5	0.42

* Note: Preliminary design parameters are subject to change as new information becomes available.

DWR (1978), in the West Sacramento Valley Fault and Seismicity Study, Glenn Complex, Colusa Reservoir, and Berryessa Enlargement, summarized what was known at that time about the Design Earthquake for these four projects. After considering the following faults - San Andreas, Hayward-Rodgers Creek-Healdsburg-Maacama, Green Valley-Cedar Roughs, Cordelia-Wragg Canyon, and Winters-Vacaville, the Foothills fault system, and RIS - they concluded that the MCE for the Glenn Reservoir Complex is a RIS earthquake of M6 resulting in 0.29g acceleration. A "Winters" type earthquake of M7 at a distance of 25 miles was also considered, resulting in a 0.14g acceleration. They did not consider the possibility that such a quake could be centered at depth directly underneath the dam. For this study we selected an M7 occurring directly under Newville Dam at a depth of about 6 miles as the Design Earthquake for the Thomes-Newville Project. WLA believes this magnitude to be conservative, based on the short length of the underlying thrust fault (Jeff Unruh, personal communication). However, they also believe that the closest approach may be closer than 6 miles.

ESA (1980), in their *Seismic and Fault Activity Study, Proposed Glenn Reservoir Complex*, assigned an MCE of M6.5 to RIS and to the Stony Creek fault. Both types of earthquakes could potentially occur in the reservoir area.

The Anderson Consulting Group (1997), in their *Preliminary Design Report for the Funks Creek Project*, adopted two MCEs occurring directly under the Funks Creek Dam site (Golden Gate Dam site of the Sites Project). One is based on an M_L6.5 occurring at a depth of 5 km, with a calculated PGA of 0.60, and the second is based on an M_L7 occurring at a depth of 10 km with a PGA of 0.46. The PGAs were based on an average derived from four mathematical attenuation models. WLA believes that even stronger ground shaking may occur at Sites, up-dip of a thrust fault rupture.

The Colusa Reservoir was assigned a similar RIS of M6, resulting in 0.29g and a Winters-type quake of M7 at an epicentral distance of 15 miles, resulting in an acceleration of 0.23g. They also did not consider the possibility that such an earthquake could be centered directly at depth underneath the dams. For this study we selected an M7 earthquake occurring directly under the reservoir at a depth of 6 miles on the Great Valley fault for both Sites and Colusa Reservoirs as the Design Earthquake. Selection of a Design Earthquake that occurs directly

under the dams is conservative and justified by the fact that only limited information is available; and an earthquake can occur along a wide zone of faulting and surface deformation. Peak horizontal ground acceleration for such an event is estimated to be about 0.70g, the period about 0.32 seconds, and the duration about 26 seconds.

A conservative estimate of the MCE for the Red Bank Project would be a Gorda plate earthquake of M8.3 occurring directly underneath a project damsite at a depth of 20 to 25 miles (35 to 40 km).

Reservoir-Induced Seismicity

RIS is believed to be a consideration for all of the proposed reservoirs because of the large volume of water and a depth that could exceed 300 feet. An M6.5 earthquake occurring directly under a damsite at a depth of about 6 miles is believed to be a conservative estimate of this type of event. This is based on numerous RIS events ranging from M5 to M6.5 that have been documented worldwide. The RIS event is smaller than other potential earthquakes related to the Great Valley fault or Gorda plate subduction that could occur at the damsites, and therefore is not considered to be the source of the Design Earthquake.

Liquefaction, Landsliding, and Surface Rupture

Liquefaction should not be a problem at the foundation of the proposed structures since the recommended construction would include the removal of all alluvium and colluvium from the dam footprints. The construction material will be processed and designed to have a negligible liquefaction potential.

Numerous small landslides occur in the Dippingvat, Sites, and Colusa reservoir areas. Most of these slides are shallow and small. A few slides occur in the Schoenfield, and Newville reservoir area. Landslides occur on the abutments of Sites and Colusa, but all of the landslide materials will be removed prior to construction. We do not consider the landsliding to be a serious concern at any of the proposed project sites.

Faults occur in the foundation areas of most of the proposed structures. Most of these are small transverse faults oriented roughly perpendicular to the regional structure. These faults are generally short and the amount of displacement small. The faults have been considered to be pre-Pliocene in age. However, if they are more recent, the amount of displacement that would be expected during an earthquake is expected to be less than one foot based on the total length of these features. Limited movement in the foundation can be accommodated by using conservative dam designs. DSOD requires that these faults be considered potentially active until evidence becomes available to the contrary.

WLA (1997) considered the Salt Lake fault to be inactive based on lack of Quaternary surface deformation. However, for the purpose of this investigation, the fault will be considered potentially active and subject to possible surface movement until further evidence of inactivity becomes available.

Field work during this study suggests that the fault is a zone of folded, faulted, and sheared rock that may be wider than the actual mapped trace. Gas seeps and salt springs occur within this zone. The zone is also a structural discontinuity between the middle Cretaceous sedimentary rocks found at the damsites and Lower Cretaceous rocks found farther to the west. One of the numerous shears associated with this zone appears to cross the foundation of the Sites Dam site. It is possibly a continuation or splay of the Salt Lake fault, as mapped by Brown and Rich (1961).

Recommendations

We recommend that the dam design for any of the four proposed projects be conservative and that elements of the Phase II Fault and Seismic Hazards Investigation be instigated. The seismic risks at these projects are not that well known. The following are a number of conservative design considerations that can be implemented. This is not meant to be a state-of-the-art discussion, but a brief list of design factors that can be implemented to reduce the risk of dam failure.

All of the major dams of the four projects are tall, nearly 300 feet. Other things being equal, the higher the dam and the deeper the water, the greater the hazard of RIS, foundation shear failure, abutment slides, large slides into the reservoir, embankment cracking and concentrated leaks, and crest settlement and overtopping (Sherard 1966). These failure modes are most prevalent during earthquakes.

The first consideration in dam design is foundation preparation. It is recommended that all soil, alluvium, colluvium, and terrace deposits be removed from the dam footprint, and that the dam be founded entirely on rocks of the Great Valley sequence (GVS). The reason for this is the potential for the alluvial materials in the foundations to fail by shear or liquefaction during an earthquake. This requires the removal of large quantities of these unconsolidated materials, particularly at Golden Gate Dam. Here terrace deposits are about 20 feet thick and cover much of the channel section.

Landslides also occur at some of the damsites. These should be removed. Most of the removed alluvial, colluvial, and landslide material can be used within the random fill part of the dam. Fault breccia and gouges should be excavated as deep as is reasonable and backfilled with concrete.

Dam design should include most of the following conservative design considerations:

- Protection from overtopping, including extra freeboard and a well-protected downstream face. Earthquake-produced landslides and seiches are capable of overtopping the dam and causing erosion on the downstream face and possible failure of the dam. A thick blanket of large riprap provides protection from this type of event.
- Excellent internal drainage, including both horizontal and vertical drains for moisture and leakage control to prevent piping and liquefaction.
- Excellent zoning with wide transition and filter zones to aid in the sealing of earthquake- or fault-induced fractures. The zones should extend all the way

to the top of the dam. The filter zones should be well graded with a mix of fine sand to gravel sizes. The finer transition material should also have an appreciable percentage of gravel to seal fractures and prevent piping. This may require processing the natural construction material deposits by sieving and washing. The strongest foundation material should be placed on the downstream toe where it will reduce the potential for embankment slumping.

- Gentler embankment slopes to increase stability, since the steeper slopes are generally more susceptible to failure. All materials should have high compactive effort to 95 percent relative compaction or more.
- Core containing plastic soils for high cohesion and minimal erosion. The core should not contain zones with clean sand or silt. For inorganic clays, the leakage resistance is probably strongly dependent on the Atterberg limits - the higher the plasticity index, and the higher the position above the A-line, the higher the leakage resistance. A coarse component of gravel would help to seal any cracks developed during an earthquake.
- Outlet facilities capable of releasing a large part of the reservoir in a short time. This would allow the rapid drawdown of the reservoir in case the dam is damaged during an earthquake. DSOD requires outlet facilities capable of evacuating 10 percent of the maximum reservoir height in ten days. Spillways should also be oversized in case of landslide-generated waves, reduced-reservoir capacity from large landslides, and seiches.
- Use of ungated, open spillways on stable rock instead of gated spillways, tunnels, or glory holes. Damage during earthquakes may make gated spillways inoperable. Tunnels or glory holes may become blocked, offset, or collapsed and would be difficult to repair during emergency conditions.

Investigation of the Salt Lake fault should be continued and expanded to determine whether this feature is active. More work needs to be done to determine whether a lineament crossing the Sites Dam site is a continuation of faulting along the Salt Lake fault. This would include trenching across possible fault traces, seismic refraction, low-angle radar imaging, and others. These activities would be carried out in Phase II.

Dynamic analysis of proposed dam designs are needed. The essential elements of such analyses are as follows: (1) an analysis of the static stresses developed in individual elements of the embankment before an earthquake; (2) the use of a dynamic finite element analysis procedure, with strain-dependent properties to allow for the nonlinear stress-strain characteristics of the embankment and foundation soils, which would determine the dynamic stresses developed in individual elements of the embankment; (3) the use of cyclic loading triaxial compression test data to determine the response of the soil elements in the dam to the induced stresses; and (4) consideration of progressive failure effects by determining the redistribution of dynamic stresses after liquefaction of 5 percent strain has developed in any soil element (Seed, in DWR 1974).

Low level, low-sun-angle aerial photography analysis and side-looking radar should be done in addition to Landsat and stereo aerial photo analyses.

Detailed laboratory testing of construction and foundation materials should be done. Compaction and remolded triaxial shear tests should be done on core materials. Relative density or compaction, in the absence of any other data, is perhaps the single most important item to be used in judging a soil's dynamic stability.

Regional Geology

The proposed projects are in the western foothills along the edge of the Sacramento Valley. The rocks underlying the damsites are part of the Great Valley geologic province, which is mostly sandstone, mudstone, and conglomerate of the Cretaceous GVS.

Geomorphic Provinces

The Great Valley geologic province is bound on the west by the Coast Ranges province, to the north by the Klamath Mountains province, to the northeast by the Cascade Range province, and to the east by the Sierra Nevada province. The location of the various geologic provinces in Northern California is shown in Figure 3. Figure 4 shows the North American geologic time scale.

Great Valley Province

The projects lie along the western edge of the Great Valley province, a 400-mile-long by 60-mile-wide sedimentary basin positioned between the Sierra Nevada, Klamath Mountains, Cascade Range, and Coast Ranges.

Along the west side of the Sacramento Valley, rocks of the Great Valley province include Upper Jurassic to Cretaceous marine sedimentary rocks of the GVS, fluvial deposits of the Tertiary Tehama, Quaternary Red Bluff, Riverbank, and Modesto formations, and Recent alluvium.

Rocks of the GVS form an asymmetric south-plunging syncline, with a steeply dipping western limb and a gently dipping eastern limb. The west side has eroded to form a series of northwest-trending, east-dipping ridges of sandstone and conglomerate separated by valleys underlain by siltstone and mudstone. Water gaps in the sandstone and conglomerate ridges form the damsites for all four proposed projects.

The basement of the GVS is believed to be basaltic ocean floor consisting of flows, dikes, gabbroic plutonic rocks, and serpentinites and is commonly referred to as the Coast Ranges ophiolite. The ophiolite is middle Jurassic in age and is believed to be the oceanic basement of a forearc basin. Most of the ophiolite is fragmented and stratigraphically thin. The contact with the overlying sedimentary rocks is believed to be depositional in some places but faulted by the Stony Creek fault in other areas.

The GVS formed from sediments deposited within a submarine fan in the forearc basin environment along the continental edge. Sources of the sediments were the Klamath Mountains and the Sierra Nevada to the north and east. Limited lateral extent and the grading of one unit into another are characteristic of this type of depositional environment.